UPGRADE OF THE LHC SCHOTTKY MONITOR, OPERATIONAL EXPERIENCE AND FIRST RESULTS

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Abstract

The LHC Schottky system allows the measurement of beam parameters such as tune and chromaticity in an entirely non-invasive way by extracting information from the statistical fluctuations in the incoherent motion of particles. The system was commissioned in 2011 and provided satisfactory beam-parameter measurements during LHC run 1 for lead-ions. However, for protons its usability was substantially limited due to strong interfering signals originating from the coherent motion of the particle bunch. The system has recently been upgraded with optimized travelling-wave pick-ups and an improved 4.8 GHz microwave signal path, with the front-end and the triple down-mixing chain optimized to reduce coherent signals. Design and operational aspects for the complete system are shown and the results from measurements with LHC beams in Run II are presented and discussed.

INTRODUCTION

The LHC Schottky system was developed and commissioned in 2010 as part of the U.S. LHC Accelerator Research Program (LARP) [1]. It can perform non-invasive measurements of machine tune, chromaticity, momentum spread and emittance [2]. In contrast to standard methods for measuring these parameters, the Schottky system does not require additional excitation of the beam in any way. Hence it is well suited as a diagnostic tool during physics runs, where beam emittance needs to be kept at a minimum.

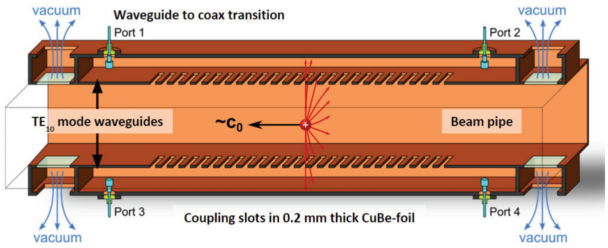

Figure 1: Internals of a LHC Schottky pick-up. Source: [3].

Most of its components, including the slotted waveguide pick-ups, the compensation path and the bunch by bunch gating circuit, have been upgraded during several technical stops since its first installation. This paper will give an overview of the current state of the system, detailing completed modifications and planned future upgrades.

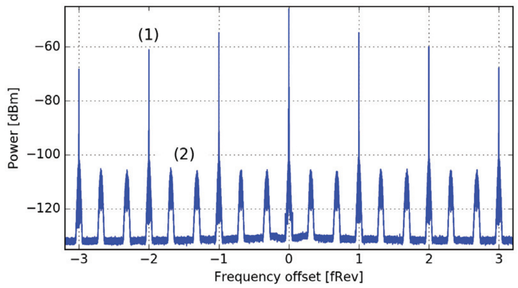

Figure 2: Schottky signals on a spectrum analyzer (LHC ion run 2015). The x-axis has been normalized to $f_{\mathrm{rev}} = 11.2$ kHz. Note how the coherent revolution lines at (1) can be orders of magnitude higher than the incoherent Schottky sidebands at (2).

SYSTEM OVERVIEW

A block diagram of the LHC Schottky system is shown in Fig. 3. The function of each component along the chain will be discussed in the following subsections.

Beam Pick-ups

The pick-ups have been designed to couple to the beam at $f_c \approx 4.8$ GHz with a bandwidth of $BW_{3\mathrm{dB}} > 500$ MHz. The choice of center frequency is a trade-off, avoiding strong coherent signals at lower values, and overlapping Schottky bands at higher values of f_c. The bandwidth was selected for effective gating on single bunches spaced by 25 ns. The LHC is equipped with 4 such pick-ups, one for each beam and transverse plane. Each one consist of two TE$_{10}$ waveguides, which are placed on opposite sides of the beampipe, as depicted in Fig. 1. A 0.2 mm thin slotted copper beryllium (CuBe) foil provides coupling to the electromagnetic (EM) field of the particle beam [1]. These pick-ups were redesigned and upgraded during the long shutdown in 2014. One problem was the different thermal expansion coefficient between the aluminium bulk material and the CuBe foil. During the bake-out procedure, the two parts elongated at different rates, leading to plastic deformation and a warping-effect of the foil. This problem was effectively resolved by machining the new pick-up bodies from CuBe bulk material. Further improvements consist of a revised slot geometry and hand-optimized waveguide to coaxial transitions, each one achieving a return loss of better than 20 dB [3].

Compensation Path

The function of the compensation path is to provide common mode rejection from a constant beam orbit offset or asymmetry in the waveguide structures and cabling. This minimizes the amplitude of unwanted ‘coherent lines‘, which would otherwise saturate the downstream microwave ampli-

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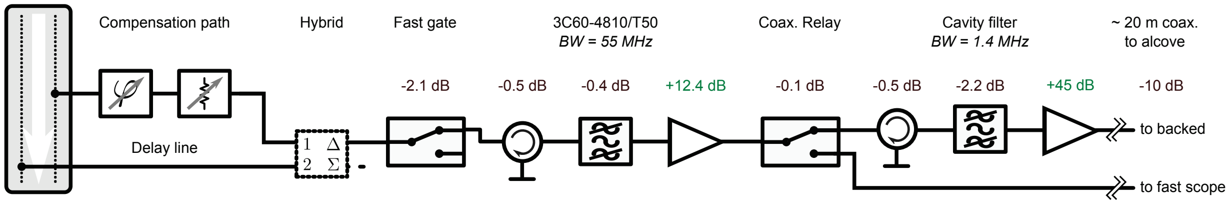

Figure 3: Block diagram of the LHC Schottky front-end electronics, which are installed directly on top of the pick-ups.

fiers. The strong coherent lines and the weaker transverse Schottky sidebands are clearly visible in Fig. 2, which depicts a spectrum analyzer measurement during the 2015 lead-ion run. These coherent lines at the revolution frequency originate from the bunched nature of the beam, with their amplitude at 4.8 GHz dependent on the bunch shape [2]. Rejection is achieved by a 180° hybrid and an electrically adjustable delay line and attenuator to compensate errors in phase and amplitude at the hybrids inputs. This makes it possible to keep mismatches on the two cables between pick-up and hybrid below 1 ps in electrical length and 0.25 dB in amplitude. It also allows compensation of an off-center beam position.

During the Schottky upgrade, the electrical length of all critical cables in front of the hybrid were verified and re-matched. Laboratory measurements indicate that the upgraded system can provide up to 40 dB of common mode rejection over a bandwidth of > 1 GHz, which results in a significant reduction of unwanted signal power.

Fast Gating

After the compensation path, a fast gating circuit will be installed to minimize the influence of unwanted signals during the time when there is no bunch in the pick-up. These signals have been observed on oscilloscope measurements, as shown in Fig. 4 and are especially visible during high intensity physics fills when the compensation path is well tuned. They appear as a ringing artifact and may be caused by microwave modes propagating along the beampipe. It has been found empirically that these signals do not contain Schottky information but do contribute to the saturation of downstream amplifiers.

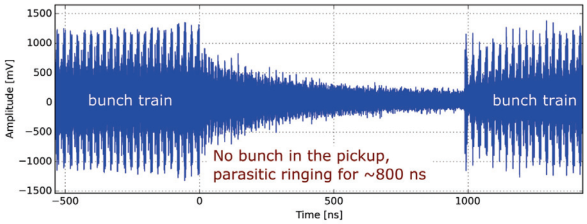

Figure 4: Signal at the difference output of the hybrid measured on a 60 GS/s oscilloscope during a physics run with protons (fill #4519). A ringing effect is visible, which may originate from waveguide modes in the beampipe.

The gating circuit has been designed and built at CERN. It is based on the *HMC547LC3* chip from analog devices and a *THS3202* current feedback amplifier to generate its control voltage. The typical switching time in this configuration was measured to be in the order of 1 ns. By designing the circuit on a microwave substrate, less than 2.1 dB insertion loss at 4.8 GHz was achieved. To generate the trigger pulses for the gates of all 4 pick-ups, a trigger generator in FMC form-factor was developed. It provides two independently programmable TTL output channels sharing a clock and trigger input. Delay and pulsewidth can be controlled with sub-ns resolution while the signal path has been optimized for low jitter [4].

Filtering and Amplification

Compared to the previous version of the front-end [5], two bandpass filters and two low noise amplifiers will be installed to provide gain and selectivity. The two staged approach is a good compromise between noise-figure and dynamic-range. A commercial bandpass filter ($BW_{3dB} = 55$ MHz) reduces the peak voltage in time domain due to its impulse response. The first amplifier is of type *GRF5020* and provides a modest amount of gain (G=12 dB) with very high linearity (1 dB compression point > 30 dBm). It compensates for the losses of the second filter, which is a custom made microwave cavity of $BW_{3dB} = 1.4$ MHz that drastically reduces the integrated spectral power for all components downstream. The second amplifier provides high gain (G=45 dB) to overcome the losses of the coaxial cables from the tunnel to the alcove. Furthermore the signal power at its output is large enough to render the added noise from all components downstream (backend, downconverter, ADC) negligible. Isolators were added in front of both filters to absorb reflected stop-band signals. A fast oscilloscope may be switched into the signal path to observe and fine-tune the function of the gating circuit. A cascade analysis of the complete receiving chain has been carried out, taking the gain, 1 dB compression levels and signal to noise ratios along the chain into account. Special care had to be taken for modelling the filters. The input signal is pulsed, so their impulse response will reduce the peak signal voltage in the time domain. The highest power level along the chain was predicted at the output of the second amplifier. For the worst case instantaneous input power of 17 dBm (1.5 V peak), there is still a 5 dB margin with respect to its 1 dB compression point.

PERFORMANCE WITH BEAM 2015

A typical Schottky spectrum for protons at the injection energy of 450 GeV is shown in Fig. 5. Note that emittance encodes into area, tune into distance and chromaticity into width differences between the transverse sidebands [2]. The gating circuit was used to compare a colliding and non-colliding bunch. A slight tune-shift is visible in Fig. 5.

Furthermore, the fine-structure within the Schottky spectra disappears due to the smoothing effect of the increased tune-spread in collision [2]. A typical spectrum for ions is shown in Fig. 6. At injection energy (black), the 3 Schottky bands are close to overlapping, justifying the choice of operating frequency. At collision energy (purple), the area under the sidebands shrinks proportionally with the reduction in geometric emittance. The shift between the injection and collision tune working point is clearly visible. The spectrogram measurement in Fig. 7 shows how these parameters change over time.

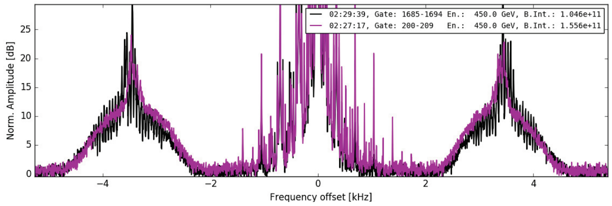

Figure 5: Nominal proton bunch at 450 GeV. **Black**: not colliding. **Purple**: colliding. Fill #4043.

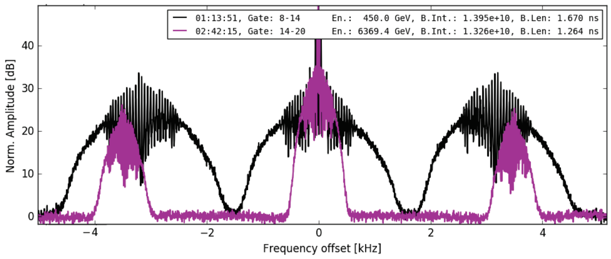

Figure 6: **Black**: Nominal ion bunch at 450 GeV. **Purple**: 7 TeV. Fill #4712.

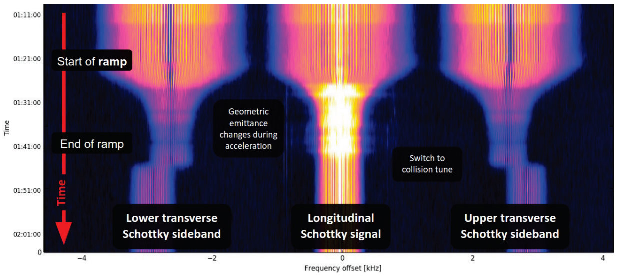

Figure 7: Evolution of Schottky signals throughout the ramp during an ion run. Fill #4712.

Although Schottky spectra are rich in information, significant signal processing needs to be done to extract numerical values reliably. As a first step to tackle that challenge, reference data has been acquired which allows cross-calibration with the default tune, chromaticity and emittance measurement methods. With this data-set, a simple data extraction algorithm based on gaussian curve-fits has been tested [6]. For given beam conditions it was possible to extract both tune and chromaticity values (shown in Fig. 8). Nonetheless, this simple method is highly dependent on how the data was pre-processed (cut-off threshold to remove unwanted peaks & smoothing) and requires substantial manual parameter-tuning. Nevertheless this reference data will now allow the development of other, more automated data-extraction algorithms, that will work reliably under a wide range of beam conditions.

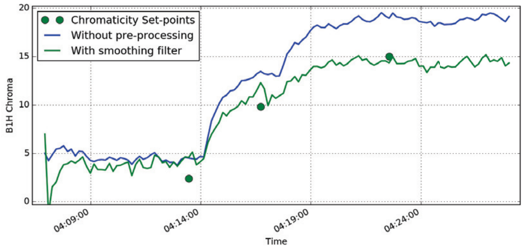

Figure 8: Extracted chromaticity from Schottky data by curve-fitting. Protons at injection energy. Fill #4275.

CONCLUSION

During the 2015 runs, the amplitude of the transverse Schottky sideband was typically 30 dB above noise level for ions, 15 dB for protons at 450 GeV and 5 dB for protons at 7 TeV. The most significant limiting factor were artifacts due to saturation of the front-end amplifiers. This was caused by high amplitude coherent signals, which were insufficiently rejected by the compensation path and exceeded the dynamic range of the system. The new 2016 front-end electronics addresses these issues with a fast gating scheme, higher linearity amplifiers and a cavity filter with narrower bandwidth – all leading to an effectively increase in dynamic range. The new electronics is foreseen to be installed in June 2016.

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